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EVALUATION OF BRIDGE DECK PROTECTIVE SYSTEMS

Final Report

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16. Abstract

The combined results of two studies designed to determine the cost-effectiveness of several alternate bridge deck protective systems are presented. A total of 15 installations were evaluated including nine waterproofing membranes (with bituminous overlays), three latex modified concrete overlays, one low-slump/high-density concrete overlay and two penetrating sealers (one system). The time-in-service of these installations ranges from about 4 to 14 years. The study findings indicate that all of the systems, with the exception of the concrete sealer, are viable restoration methods that can be used to extend the life of a lightly to moderately deteriorated deck an estimated 10 to 15 years. The performance of the sealer was unsatisfactory since it did not provide the expected protection against water and chloride intrusion.

Life-cycle costing techniques were used to determine the economic benefit to the Department when employing either of the systems to delay complete deck replacement for varying periods of time.

Recommendations for future use of these systems and cathodic protection, a potentially viable alternate, are presented.

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Conclusions

Based on the performance testing and cost analysis of several alternate bridge deck protective systems over a period of 14 years, the principal conclusions from this study were:

1. Both the membrane systems and the rigid overlays appear capable of extending the life of a deck a minimum of 10 to 15 years.
2. The latex modified concrete overlay (LMC) is the most cost effective of the systems evaluated.
3. Recent latex modified concrete installations have been effective against chloride penetration after three years in service.
4. Membrane systems and rigid overlays do not stop active corrosion.
5. Despite durability problems with the bituminous overlays, membrane systems appear to be effective in slowing corrosion activity and reducing chloride penetration.
6. Chem-Trete silane surface treatment did not provide the expected protection against water and chloride intrusion.

Recommendations

1. Current Department bridge deck rehabilitation policy using membranes and latex modified concrete overlays should continue where relatively short-term protection is required and/or the use of cathodic protection is not feasible (i.e., when route expansion/realignment is planned or complete deck replacement is imminent).
2. Despite the disappointing performance of Chem-Trete, penetrating sealers should continue to be evaluated by the

Department for use on bridge surfaces other than the wearing surface.

3. Where it is deemed cost effective, cathodic protection should be used on those decks exhibiting light to moderate corrosion damage (see guidelines, p.34).

PART ONE: INTRODUCTION

1.1 Problem Statement

There has been insufficient information available to adequately predict the extent to which bridge deck restoration methods applied to deteriorated decks can control corrosion and thus achieve an economic extension of the life of the structure.

1.2 Objectives

The primary objective of this research was to determine the cost-effectiveness of various protective systems.

The specific objectives of the separate studies covered herein were:

1. To determine the long-term effectiveness of waterproofing membranes and modified concrete overlays in controlling corrosion and thus preventing subsequent deterioration of decks subjected to deicing chemicals.

2. To determine under which circumstances the use of waterproofing membranes on salt-contaminated decks is a viable alternate to extensive reconstruction of deteriorated decks.

3. To determine (a) the effectiveness of Chem-Trete silane surface treatment in the preventing the intrusion of chlorides and moisture into concrete decks, and (b) to estimate the economic benefits to be derived from the use of Chem-Trete as an alternate to currently approved protective systems (i.e., latex modified concrete overlays and waterproofing membranes).

1.3 Background

Premature deterioration (spalling) of concrete bridge decks resulting from accelerated corrosion of the reinforcing steel is recognized as a major problem both nationally and in New Jersey. The cost of maintaining or restoring these structures to a serviceable condition are substantial.

Such deterioration became widespread several years after many states adopted the "bare roads year round" policy during the mid-1960's, increasing the use of deicing salts to keep the decks clear of ice and snow. Subsequently, chlorides were identified as the primary factor in causing the problem.

It was found that the chlorides ion destroys the normal passive state of the steel in the alkaline concrete environment resulting in corrosion. Since the corrosion/deterioration process is well documented,[1,2], it will not be covered here.

Primarily, this report will summarize New Jersey's experience in seeking to determine the most cost-effective method of protecting concrete bridge decks from deterioration.

The combined results from two different studies which evaluated the in-place performance of several protective systems will be presented.

The first study was entitled "Long-Term Monitoring of Bridge Deck Protective Systems" (Project No. 7799, Item 12). This project was initiated in 1980 to allow for the continued monitoring of systems which had been under study in an earlier research effort by Weed[3]. This effort was renewed because the end-point of performance history was not known, thus preventing an

accurate assessment of cost-effectiveness. This was particularly true of the waterproofing membranes.

In 1982, a second phase was added to the above study to determine the effectiveness of Chem-Trete, a silane-based sealer. This sealer had been promoted by the FHWA as a more economical alternate to latex modified concrete overlays on decks which were not heavily salt-contaminated[4].

The second study, "Experimental Cost-Effective Reconstruction" (Project No. 7799, Item 7), examined the effectiveness of waterproofing membranes on salt-contaminated decks. The FHWA required follow-up performance testing for this alternate approach to complete reconstruction. Interim performance information and project details are provided in earlier reports[5,6].

At the final evaluation (winter 1985), these installations had been in service from about 4 to 14 years. In total, 15 installations were evaluated including nine waterproofing membranes, three latex modified concrete overlays (LMC), two concrete sealers and one low-slump/high density concrete overlay (LSHD).

A list of the study installations is provided in Appendix A.

PART TWO: METHODS OF EVALUATION

As per FHWA guidelines[4], either annual or biannual performance evaluations were conducted on the studied systems after restoration. Before 1981, only visual inspection and a modified electrical resistance test were used. Subsequently, corrosion testing, chloride content analysis and an improved electrical resistance test method were employed in addition to visual inspection. Performance testing was conducted by the Department's Bureau of Engineering Services; coring was performed by the Bureau of Materials.

2.1 Physical Condition Survey

Visual inspection of the riding surface and underside of the decks were routinely conducted to determine general condition. The final evaluation of the membrane systems further included inspection of the underlying concrete deck. This was accomplished at several locations where a 1 sq. ft. area of the bituminous overlay was removed to permit chloride sampling. Hammer sounding was also performed to detect delamination at these locations.

2.2 Chloride Content Analysis

The chloride content at the level of the top mat of reinforcing steel (1 to 2 inches) in the study decks was determined from drilled powder samples. The samples were obtained and tested in accordance with the procedure reported by H. A. Berman [7].

In the second study (equipment was not available in the first study), samples were taken from randomly selected locations on each deck prior to installation of the protective system and at the final inspection.

A chloride content of 2.0 lbs/cy of concrete has been generally accepted[1] as the threshold at which corrosion is likely to occur and above which it is probably more economical to remove and replace the concrete. However, it has been determined that a content as low as 1.1 lbs/cy is sufficient to destroy the passivity of steel and initiate corrosion[8]. Both threshold levels will be discussed herein.

2.3 Electrical Potential Survey

This testing was performed in accordance with ASTM C-876-77, "Half-Cell Potentials of Reinforcing Steel in Concrete". The method covers the estimation of the electrical potential of reinforcing steel in concrete for the purpose of determining corrosion activity. Measured potential values greater than -0.35 volts indicate a greater than 90 percent probability that corrosion is occurring in a certain area at the time of measurement. Values between -0.20 and -0.35 volts indicate corrosion activity is uncertain. Values less than -0.20 volts indicate a greater than 90 percent probability that no corrosion is occurring at that time and location. Since the potential of the rebar is almost always active in relation to the $Cu/CuSO_4$ reference electrode used in this test method, more active corrosion gives a more negative potential (e.g., -0.35v > -0.20v). However, for simplicity, the sign of the potential will be disregarded with data presented herein. Accordingly, a numerically larger value indicates a more active potential.

This technique has proven very useful for detecting areas of corrosion or potential corrosion prior to any visible signs of distress. Although the validity of this technique has been

verified by a number of researchers, caution must be exercised in the interpretation of data because of measurement error[5] .

2.4 Electrical Resistance Survey

This nondestructive method covers the measurement of the waterproofing effectiveness of membrane/pavement systems when applied to concrete decks. The basic concept involves measuring (with an ohmmeter) the gross electrical resistance between an electrode placed on the saturated (by water sprayed on a specified area) top surface of the membrane and the top mat of reinforcing steel to which it is electrically connected. Readings are interpreted to indicate variation in the imperviousness of the membrane and the relative degree of wetness in the underlying concrete surface. The degree of wetness is inversely proportional to the resistance reading. More specifically, observed resistances of 500,000 ohms and greater indicate "excellent" performance; measurements ranging from 500,000 to 100,000 ohms are considered "questionable" while a reading below 100,000 ohms indicates "poor" performance. The above criteria was developed by California researchers Spellman and Stratfull.

PART THREE: RESULTS AND DISCUSSION

This section presents the analysis and interpretation of performance data collected from the study installations. A summary of data from the final evaluation of each installation is presented in Appendix B. Three of these data sets, chloride content, electrical potential and electrical resistance are summarized by protective system in Appendix C (Tables 1 through 9). Pooling of these data was warranted because clarity of presentation was enhanced without loss of statistical significance in the analysis.

3.1 Membrane-Protected Decks

The nine membrane systems evaluated included seven preformed sheet types, one liquid rubberized asphalt and one tack coat membrane. At the final evaluation, these installations had been in service from seven to thirteen years. Detailed information on the materials used , pre-construction deck condition and early performance history are provided in earlier reports[3,5].

Corrosion testing, using the half-cell potential method, was performed on several membrane systems during their first few years of exposure. However, this method was discontinued when it was realized that the procedure used (i. e., measurement from the surface of the bituminous overlay) was unreliable. Several researchers have established that in order to optimize measurement accuracy on membrane systems, it is essential to establish contact with the underlying concrete deck surface[9]. This requires drilling holes through the bituminous overlay and membrane to accommodate the half-cell probe. The Department's Bridge unit considered this procedure destructive and consequently discon-

tinued its use. Evaluation of the membrane-protected decks continued using visual condition assessment, electrical resistance testing and chloride content testing.

3.1.1 Condition Evaluation

Although the riding surfaces remain serviceable, poor durability has been a major problem with the membrane systems. Considerable cracking in the bituminous overlay had developed by the fifth year in most installations. Subsequently, a wide range of distress was observed including, shoving and patch deterioration.

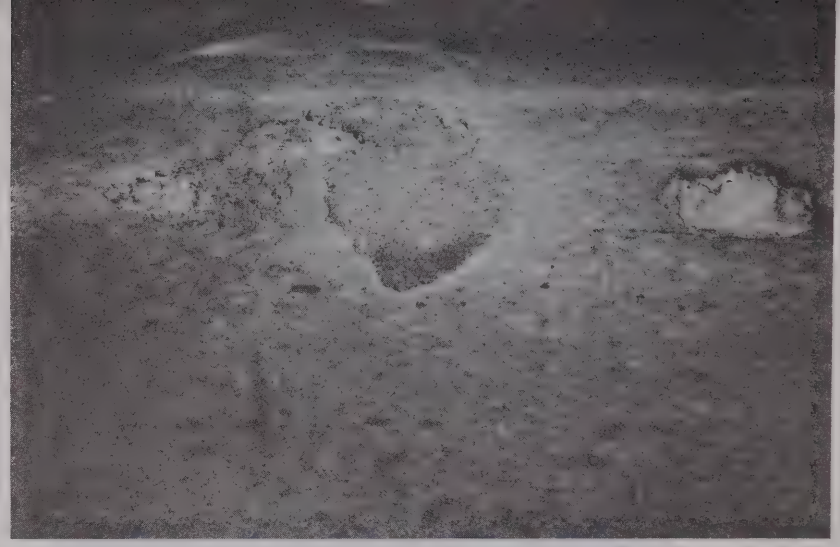
Several typical distresses exhibited by the studied membrane systems are shown in Figures 1 through 6. Figure 1C shows the shoving distress which occurred in the slow lane/shoulder area on Test Site No.7 and likely aggravated by heavy truck traffic at this site. The bituminous patch deterioration and associated membrane damage shown in Figures 1B and 1D is largely attributed to a difficult patching operation[6].

The results of the final condition evaluation (Appendix B) show that most of the studied installations also exhibited rutting, delaminations in the underlying concrete, spalling and signs of leakage (stains and efflorescence) on the underside of the deck.

3.1.2 Chloride Content Analysis

The collected chloride content data (Table 1) show no significant changes (where baseline data is available) since the systems were installed. However, the results show that eight of the decks have contamination levels indicative of moderate active corrosion.

A: Patching, Patch Deterioration, Cracking

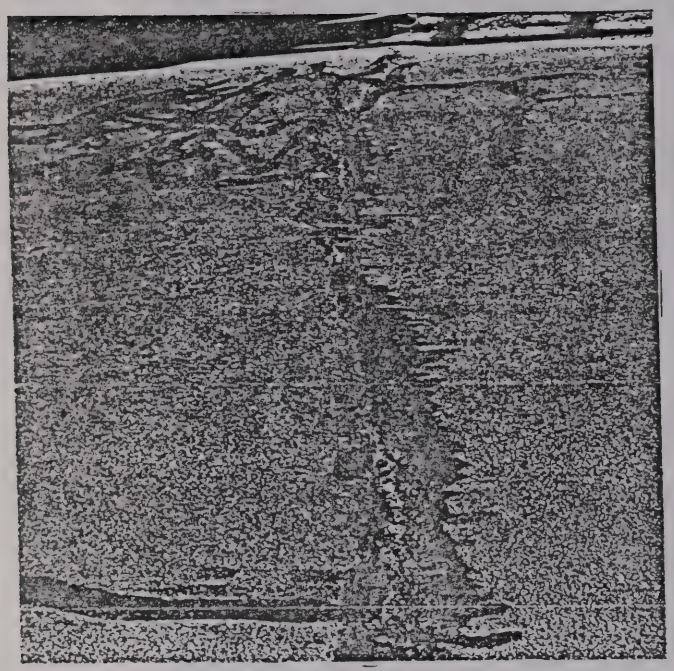


B: Patch Deterioration/Membrane Damage (exposed)

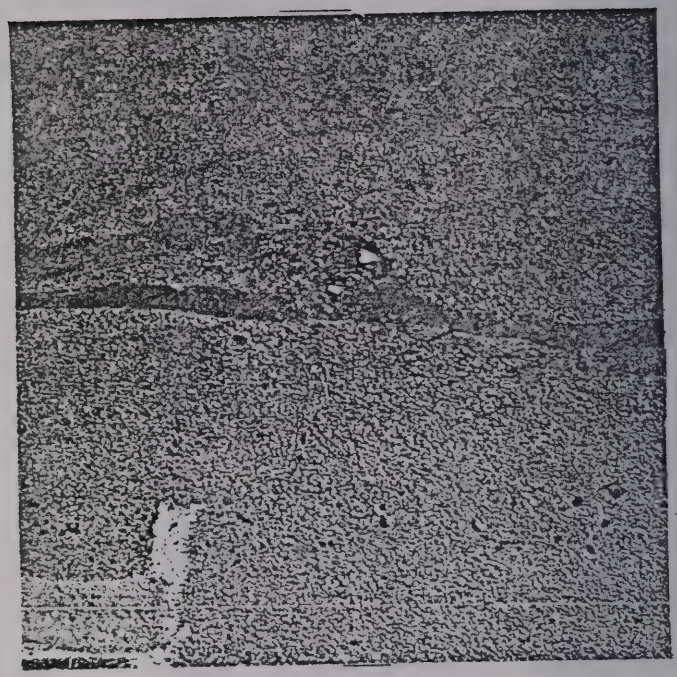
C: Shoving

D: Patch Deterioration

FIGURE 1: Bituminous Overlay Deterioration/Membrane Damage; Test Site No. 7, 8 Years in Service



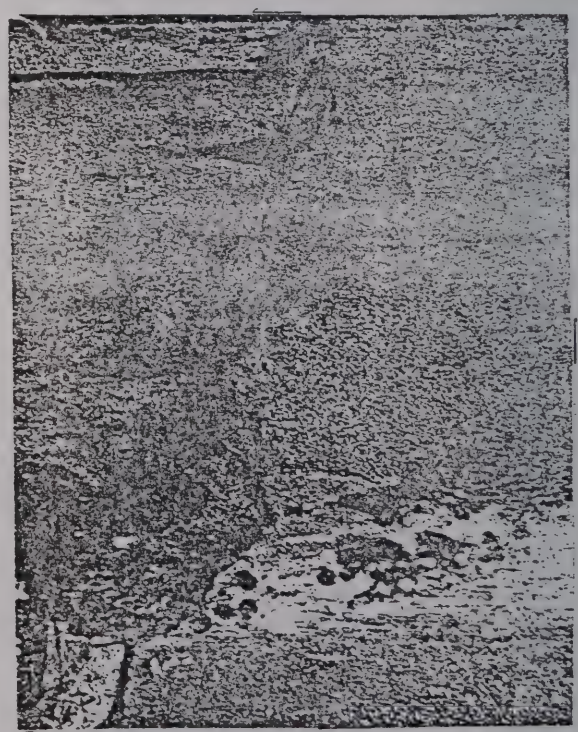
A: Sealed Cracking/Deterioration



B: Pothole/Map Cracking

FIGURE 2: Bituminous Overlay Deterioration
Test Site Nos. 2 and 3, 13 Years in Service

A: Shoving; Overlay/Membrane Deterioration



B: Patch Deterioration/Membrane Damage

FIGURE 3: Bituminous Overlay Deterioration/Membrane Damage, Test Site No. 4, 10 Years in Service

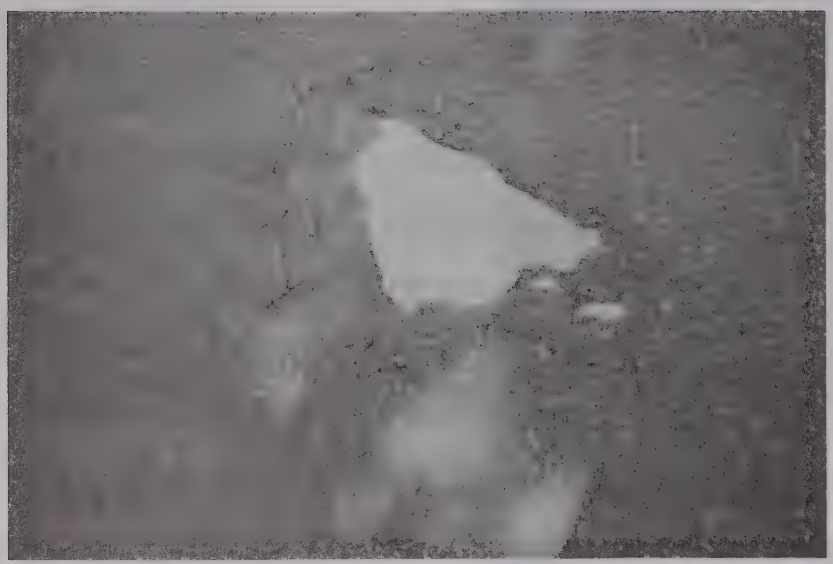
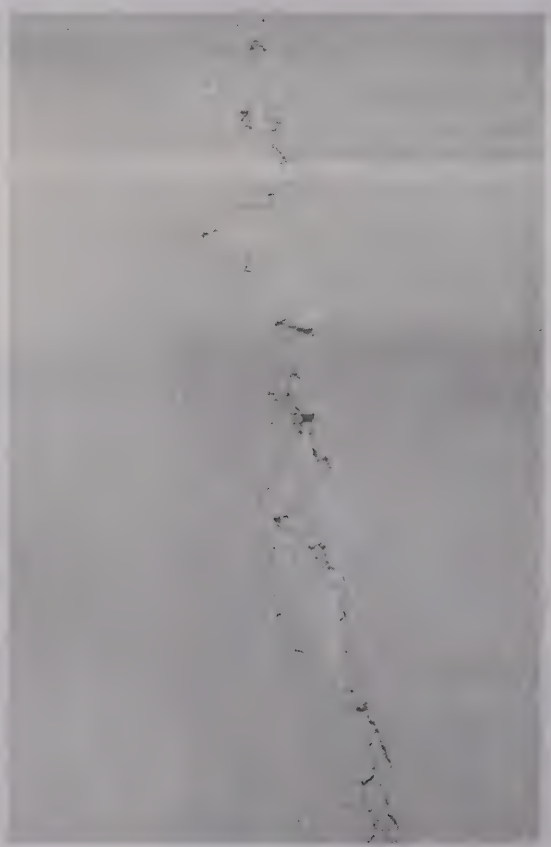


FIGURE 4: Patch Deterioration
Test Site No. 8
8 Years In Service

FIGURE 5: Cracking; Patch Deterioration
Test Site No. 9a
7 Years in Service

A: Reflection Cracking; Pothole

B: Reflection Cracking; Pothol
(Close-up of A)



C: Relection Cracking; Deterioration

D: Map Cracking

FIGURE 6: Bituminous Overlay Deterioration
Test Site No. 1; 13 Years on Service

3.1.3 Electrical Testing

The summary of electrical resistance testing in Table 2 shows that most of the systems have been generally ineffective as waterproofing barriers.

3.2 Rigid Overlays

One low-slump, dense concrete overlay (Iowa System) and three latex modified concrete overlays were evaluated. Both systems were placed in 1-1/4 inch thicknesses and designed to create a relatively impermeable barrier at the top surface of the deck.

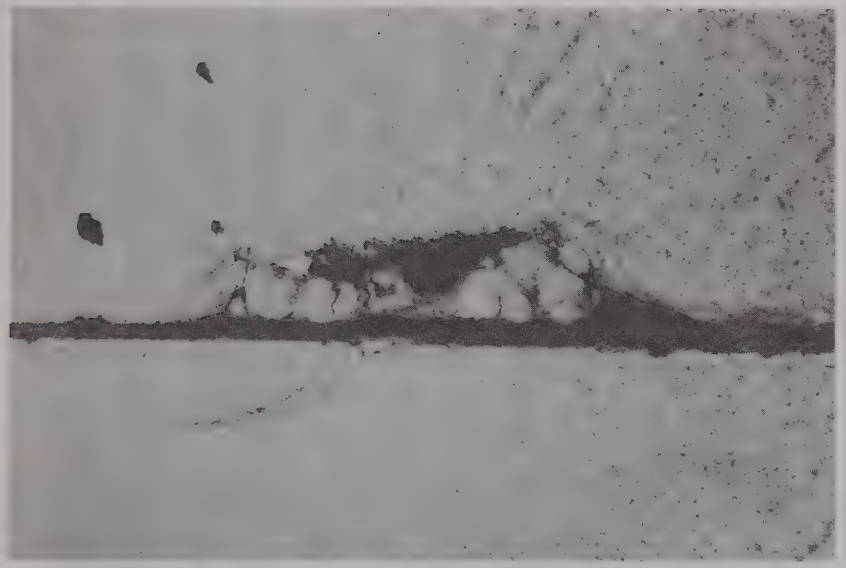
The older LMC overlays (Test Sites 5 and 6) performed satisfactorily through Weed's study (1980). Monitoring of those installations continued under Research Study No. 7799, Item 12, "Long-Term Monitoring of Bridge Deck Protective Systems."

The remaining LMC systems were installed in 1982 as part of another research effort designed to compare their effectiveness to that of Chem-Trete BSM, a silane concrete.

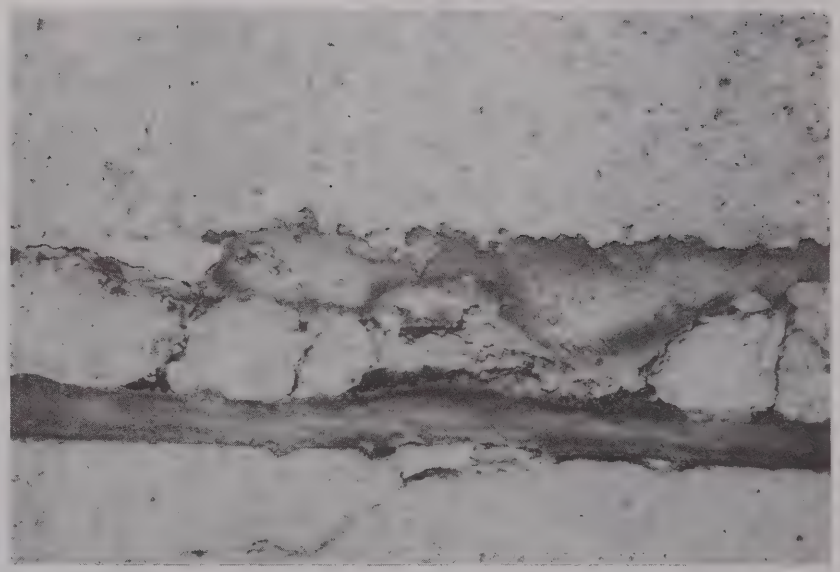
3.2.1 Condition Evaluation

The LMC overlays on Test Sites 12 and 14 were in very good condition at the final inspection (3 years exposure).

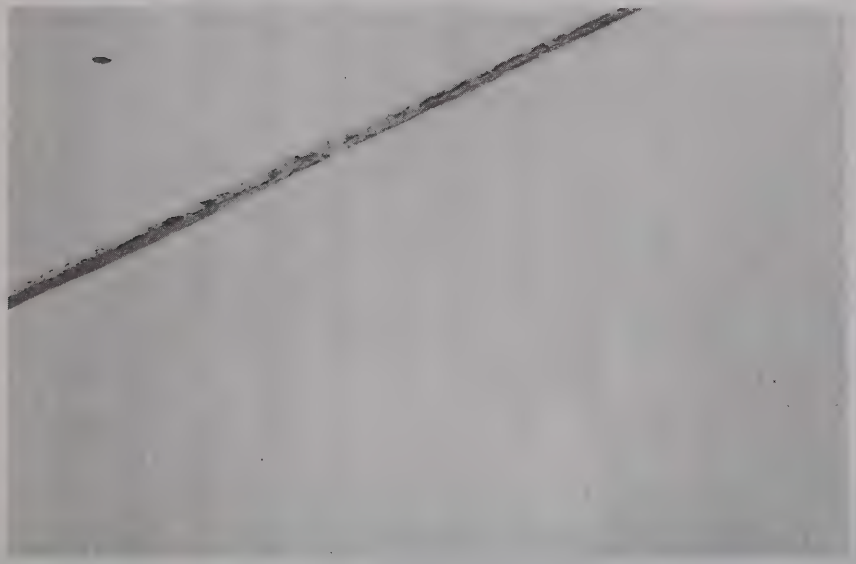
The LMC overlay on Test Site No. 5 remains serviceable, but has shown gradual deterioration. A variety of distress was observed at the final inspection including scaling, cracking, spalling, and delamination (see Figure 7). The underside of the deck exhibited hairline to narrow cracking with efflorescence and evidence of leakage at the deck joints. Weed investigated what may have been a precursor to the above distress. The investigation involved an analysis of core specimens to determine possible



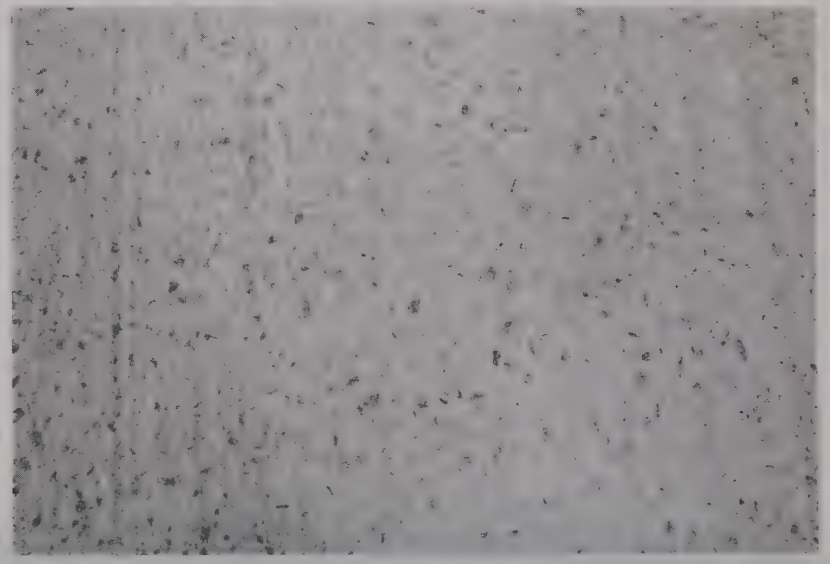
A: Joint Spalling



B: Joint Spalling (Close-up of A)



C: Concrete Patch



D: Scaling

FIGURE 7: Distress on Latex Modified Concrete Overlay; Test Site No. 5, 13 Years in Service

cause(s) for premature random cracking in half of 24 LMC overlays constructed in about the same period. It was determined that, in some cases, cracks penetrated to the top mat of reinforcing steel. The LMC manufacturer's representative offered that while localized corrosion could occur at isolated points where a crack reaches the steel, a generalized spalling condition was not a likely consequence. The unavailability of a suitable repair technique at that time and interest in learning if the condition was, in fact, harmless, prompted the decision to forego any repair attempt.

Detailed information regarding the deck condition of Test Site No. 5 before rehabilitation is unavailable. However, Weed noted that the deck was badly deteriorated and up to six inches of defective concrete was removed from several locations during repair operations.

It would be difficult to attribute the observed distress entirely to the cited premature cracking without more specific information (i.e., baseline chloride levels, level of corrosion activity, repair techniques and patching materials) on the deck condition before installation of the LMC overlay . However, based on current high chloride levels and the steady increase in corrosion activity (see B, Tables 2 and 3), it is likely that cracking contributed to the present condition by providing relatively direct paths for water and chlorides to reach the steel and cause corrosion.

It should be noted here that random cracking, associated with an inadequate curing process, continues to be somewhat of a problem with LMC overlays. However, the extent of this cracking

is typically minor in New Jersey installations due largely to our contractor's construction experience and recognition of the importance of proper and timely curing methods. Thus, the overall integrity of the LMC protective system is not compromised by the random cracking phenomenon.

The low-slump, dense concrete overlay on Test Site No. 6 exhibits light to moderate scaling, hairline cracking and several (sealed) cracks running the full length and width of the deck (see Figure 8). Development of random, as-constructed cracking in this overlay was similar to that in the LMC (Test Site No. 5), but less severe. As in the case of the latter, the cause of the cracking is attributed to the curing process. This recurrence emphasizes the critical need for proper curing procedures when special mixes are used. The cracking condition in the Iowa overlay has remained essentially stable over the past several years.

3.2.2 Chloride Content Analysis

No baseline chloride level determinations were made on Test Site 5 (LMC). However, the collected chloride data (Table 3), shows this deck is heavily contaminated: about 70% of the samples display a chloride content greater than 2.0 lbs/cy and 15% are within the 1.0 to 2.0 lbs/cy range.

The remaining LMC installations (Test Site Nos. 12 and 14) are performing well as the Table 3 data shows essentially no contamination and no changes in chloride levels after 3 years of exposure.

No baseline chloride data is available for the Test Site No. 6 (LSHD). Table 3 data shows that no samples are over the 2.0

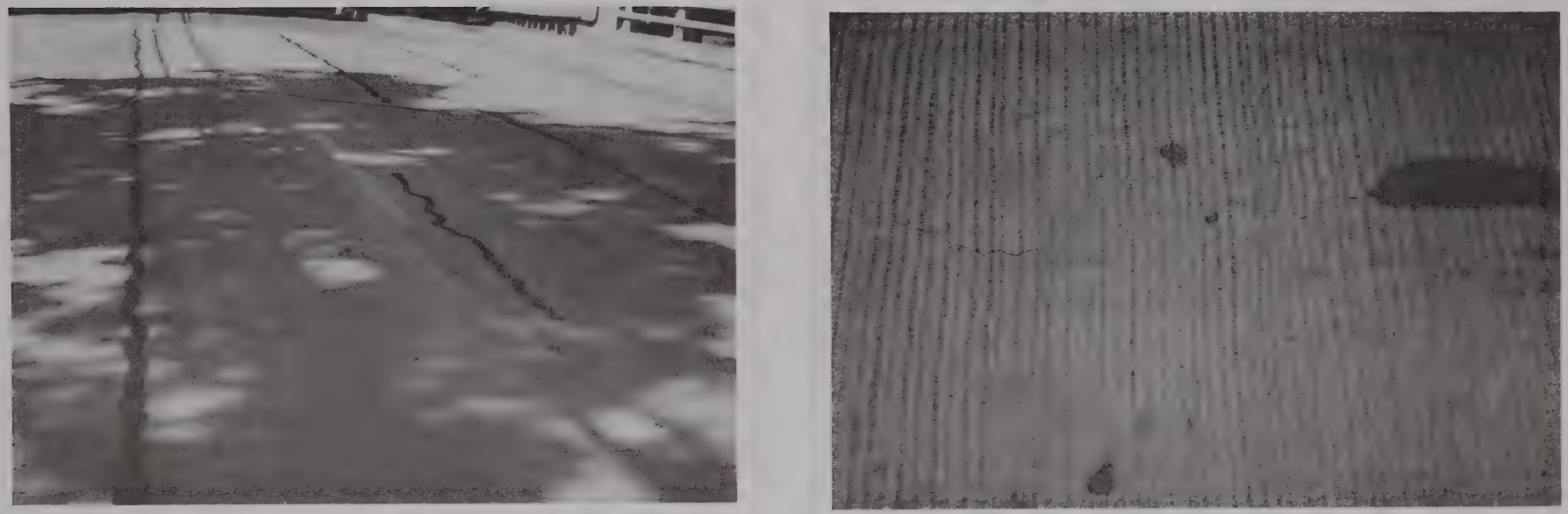


FIGURE 8: Sealed and Random Cracking; Test Site No. 6
Iowa System: Low-Slump, Dense Concrete)
9 Years in Service

lbs/cy threshold, while 40% are in the 1.0 to 2.0 lbs/cy range. This marginal chloride contamination level and the absence of corrosion activity (explained in the following section) seem to be reflected in the relatively stable physical condition cited in the preceeding section (3.2.1)

3.2.3 Electrical Testing

The results of half-cell potential testing are presented in Table 4. Test Site No. 5 (LMC) data shows a significant (tenfold) increase in corrosion activity over the past five years. Current levels indicate that extensive active corrosion is taking place. The latter is not surprising in view of the severe, as-constructed cracking in this deck discussed earlier (see section 3.2.1).

No active corrosion has occurred in Test Sites 12 and 14 (LMC) after three years in service.

Half-cell results from Test Site No. 6 (LSHD) indicate this system has shown good resistance to corrosion after eight years in service.

The results of electrical resistance measurements, summarized in Table 6, surprisingly indicate that the rigid overlays are no more effective as waterproofing barriers than the previously discussed membrane systems.

3.3 Sealer-Treated Decks

3.3.1 Background

In conjunction with nationwide efforts during the mid and late 1970's to find cost-effective protection, the FHWA[10] identified Chem-Trete BSM, a penetrating sealer as an alternate, low-cost treatment which held promise. Subsequently, experimental

use of Chem-Trete was encouraged for both new and existing (sound, air-entrained) bridge decks.

The results of laboratory testing by the FHWA and various states indicated significant reductions in water absorption and chloride ion penetration of concrete treated with Chem-Trete. For example, in comparison to untreated control specimens, Chem-Trete had reportedly decreased water absorption by a factor of ten and chloride intrusion by a factor of six.

Based on the above reports, our laboratory conducted a limited evaluation of sealer products for the Department's Materials Committee. The results indicated that Chem-Trete was sufficiently effective to warrant field evaluation. Accordingly, the Department's Bridge unit, charged with monitoring the condition of structures statewide, selected four adjoining bridges (Test Sites 11 through 14) for a trial installation. The contract Route I-195, Section 1C and 2B, specified that two different bridge deck protective systems--Chem-Trete and latex-modified concrete overlays--be installed on those structures. Installation of the systems was completed in November 1982.

During the second year (1984) of the scheduled three-year evaluation, the FHWA announced a change in its position regarding the use of concrete sealers[11]. It had been established, contrary to several manufacturer's claims, that none of the available sealers penetrated concrete to an appreciable depth (i.e., greater than 1/16 of an inch). Consequently, the FHWA recommended sealers for all (non-abraded) bridge surfaces except the top deck surface. In the latter application, the thin sealer penetration would be subject to relatively rapid wear-out,

especially under high traffic volumes. It should be noted here that similar penetration results were obtained in tests conducted by the Department for this study.

Detailed information regarding the condition of the study decks prior to treatment with Chem-Trete and application data is summarized in Appendix C (Tables 6 and 7). The construction phase of the Chem-Trete study is documented in an unpublished report[12].

3.3.2 Condition Evaluation

The results of the pre-treatment visual assessment indicated both Chem-Trete decks were in generally good condition. After 2 years in service, a light scaling condition developed over about 1/3 of the wearing surface on each deck. By the end of the evaluation (3 years), this condition had spread to cover more than 1/2 the surface areas on each deck (see Figure 9).

In an investigation to determine the possible cause(s) for this scaling, cores were taken from the decks and tested for (1) water absorption (through the treated surface only) using the manufacturer's recommended method and (2) air void content as per ASTM C457, "Recommended Practice for Microscopic Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete"--Linear Traverse Method. The test results indicated that (1) the water absorbing capacity of these decks had increased significantly and was now nearly equivalent to that of the untreated control specimens (i.e., 3.6% for Chem-Trete vs. 4.4% for the control) and (2) the air void system, responsible for providing freeze-thaw resistance, was at least marginally adequate.

FIGURE 9: Typical Scaling Condition on Sealer Protected Decks
Test Site Nos. 11 & 13, 3 Years in Service

Although the exact cause of the scaling was not determined, earlier reports by the FHWA and others noted that laboratory specimens treated with Chem-Trete had shown poor freeze-thaw resistance[13]. In any event, the results of the above absorption test strongly suggests that the sealing/waterproofing capability of Chem-Trete had diminished significantly in the studied installations.

The results of wear measurements obtained annually on these decks indicated that essentially no surface wear had taken place over the three-year evaluation period (less than 0.03 in.).

3.3.3 Chloride Content Analysis

Table 7 shows the chloride content distribution at different levels in the sealer protected decks. There has been no increase in chloride content at the level of the top mat of reinforcing steel. However, at the surface to 1 inch depth, there has been marked increase in 1.1 to 2.0 lbs/cy category. The latter suggests that the sealer may not be providing adequate protection and thus migration of chlorides to the top mat of steel is imminent.

3.3.4 Electrical Testing

The results of electrical testing, summarized in Tables 8 and 9, indicates that while no active corrosion is taking place in the sealer-treated decks, Chem-Trete has been largely ineffective as a waterproofing barrier.

3.4 Expected Service Life of Protective Systems

3.4.1 Membrane and Rigid Overlays

Based on the results of this study, the membrane and rigid overlay systems are considered viable methods for extending the

life of light to moderately deteriorated decks an estimated 10 to 15 years. However, over the past several years, the latex modified concrete overlay has been the most widely used method by the Department because of its extended deck life, low permeability (resulting in minimal additional chloride penetration) and new, skid-resistant riding surface. With experience, improved repair techniques and construction practices, the performance of LMC has improved and thus a minimum life expectancy of 20 years may not be unrealistic.

3.4.2 Concrete Sealers

Chem-Trete, a penetrating concrete sealer, did not perform well in this study. However, there are several, low-cost sealers available and in use in a variety of applications[14,15]. As cited earlier (see Section 3.3), sealers generally do not penetrate concrete surfaces appreciably and therefore are not recommended for bridge wearing surfaces or abraided surfaces. They are more suited for the protection of abutments, piers, columns and use in conjunction with overlays.

In the above applications, the expected service life reportedly ranges from 5 to 10 years. The use of penetrating in another potential application is currently being investigated in New Jersey. That is, as short-term measure for improving the early age (i.e., first year exposure) freeze-thaw durability of concrete decks and barrier curb.

3.4.3 Cathodic Protection

In 1982 the FHWA recognized cathodic protection as the only rehabilitation technique known to stop corrosion in salt-contaminated bridge decks regardless of the concrete's chloride content[16]. It was further determined that cathodic protection is an effective method for the rehabilitation of decks with sound, but salt-contaminated concrete. The use of cathodic protection has been promoted by the FHWA's Demonstration Projects (No. 34) Program since 1974 and was given higher priority in 1982 after successful experimental installations in California, Oklahoma and other states. It is now acceptable for inclusion as a standard item on Federal Aid projects[17]. To date, more than 35 states and the District of Columbia have participated financially and technically with the FHWA and installed cathodic protection systems. Projects now total more than 100 nationally. In the winter of 1988, New Jersey completed the installation of cathodic protection systems on 18 structures in a major deck rehabilitation project on Interstate Route 80 in Morris, Essex and Passaic Counties in the northern part of the state.

Basically, cathodic protection uses electrochemical techniques to insure that oxidation reactions (electrical current that naturally develops when galvanic corrosion occurs) do not occur at the reinforcing steel. The application of cathodic protection to bridge decks was introduced in 1973 and the effectiveness of the technique in combating corrosion is well-documented[17,18]. The estimated useful design life of a properly designed, installed and maintained system is 30 years (with no corrosion taking place), and it can be replaced to provide an additional 30 years protec-

tion.

3.4.4 Epoxy-Coated Rebars

Although the Department has not made a formal performance evaluation of decks with epoxy-coated rebars (used in New Jersey construction since about 1973), the best available information indicates that they have performed satisfactorily. Current Department practices for complete deck replacement and new construction call for the use of epoxy-coated rebars (in the top mat of reinforcement) in addition to a latex modified concrete overlay. Research by others[18,19] suggests that epoxy-coated rebars in new construction will last the life of the structure and thus provide more cost-effective protection than cathodic protection. The latter premise is based on the fact that while cathodic protection indeed stops corrosion, other expenses are incurred for routine inspections and maintenance (i.e., costs for anode repair/replacement and electricity) during the life of the structure.

3.5 Summary of Relative Merits of the Studied Systems

Based on the results of this study, Department experience and reports by others[9], the following table was developed summarizing the relative merits (apart from costs) of the studied systems. The merits of bridge deck cathodic protection, a promising alternate, is also presented.

Studied Protective System	Advantages	Estimated Life, years	Disadvantages
Latex Concrete Overlay	Relatively impermeable; of slab; skid resistant riding surface; increases cover over reinforcing steel; several qualified contractors available.	20	Does not stop active corrosion; susceptible to shrinkage cracking.
Sealer	Relatively fast, simple installation; no specialized equipment required; minimal traffic control required.	5-10	Does not penetrate appreciably; not suited for wearing surfaces.
Membrane w/ Bituminous Overlay	Relatively impermeable; smooth riding surface; applicable to any deck geometry; several qualified contractors available.	10-15	Generally poor durability (susceptible to shoving, rutting, etc.), particularly at high traffic volume locations; not suited for badly spalled decks.
Cathodic Protection	Stops active corrosion; long service life; can be used on decks with active cracks.	30	Requires specialized contractors, inspection, periodic maintenance and monitoring, electrical power source; limited performance history.

PART FOUR: ECONOMICS

4.1 Current Estimated Costs

The following table lists approximate current costs for four different bridge deck protective systems. These cost were obtained from records provided by the Department's Design, Construction and Maintenance and Contract Administration units. The costs for Systems 1 through 3 were obtained by adding $20 per square foot for mobilization and traffic control which were not included in the data that was available. Mobilization and traffic control was already included in the data obtained for System 4.

	Protective System	Current Estimated Cost ($/s.f.)
1.	Membrane w/Bituminous Overlay	35.00*
2.	Latex Modified Concrete	40.00*
3.	Cathodic Protection w/Latex Modified Concrete Overlay	45.00*
4.	Complete Deck Replacement w/epoxy-coated reinforcing steel (top mat) and Latex Modified Concrete Overlay	60.00**

* Includes additive of $20/s. f. for mobilization and traffic control.

** Mobilization and traffic control included in raw data.

4.2 Basis of Economic Analyses

The primary goal in installing Systems 1 through 3 is to delay the time at which a complete deck replacement is required. A more expensive system can be justified only if it produces a correspondingly longer period of delay. To compare different systems, life-cycle costing techniques were used to determine the economic benefit to the Department of delaying the deck replacement for varying periods of time[20].

For example, suppose a complete deck replacement at $60/s.f. were expected to be required 10 years in the future but, due to a more effective (and more costly) repair strategy, this could be delayed until the 15th year. Because of the time value of money, there is a tangible benefit to the highway agency to delay any major expense. If this benefit exceeds the extra cost of the more effective delaying strategy, then this would be a prudent course of action. Otherwise, it would not.

To apply this type of analysis, a slightly different approach has been taken. Equation (1), which is derived in Appendix D, gives the required life (t_B) of the more expensive system in terms of the expected life (t_A) of a less expensive system. This permits the comparison of any two systems in a pairwise fashion. If experience suggests that the actual life of the expensive system would exceed the required life (t_B) obtained from Equation (1), then it would be appropriate from an economic standpoint to select that system.

Equation (1):

$$t_B = \ln(R^{tA}-D(1-R^{40})/(60+35(R^{20}+R^{30}))/\ln(R) \qquad (1)$$

in which

t_B = required life (years) of more expensive system

t_A = expected life (years) of less expensive system

D = current difference in total installed cost between the two candidate systems ($/s.f.)

$R = (1+R_{inf}/100)/(1-R_{int}/100)$

R_{inf} = average long-term annual inflation rate (percent)

R_{int} = average long-term annual interest rate (percent)

ln = natural logarithm operator

4.2.1 Systems 1, 2 and 3 Versus No Delaying Strategy

Of the three systems listed in Section 4.1 that be might used as delaying strategies, the least expensive is System 1, which includes a waterproofing membrane and a bituminous overlay at a total in-place cost of $35/s.f. For this analysis, it will be assumed that some form of repair is needed immediately. If System 1 is installed, there will be an attendant delay before complete reconstruction is required; otherwise, complete reconstruction must be done immediately.

In this case, System 1 is being compared with "no system" as a delaying strategy. The difference in cost between the systems, therefore, is simply D = $35/s.f., the total in-place cost of System 1. Since "no system" is the "less expensive system" for the comparison made by Equation (1), the expected life of the less expensive system to be used in that equation is $t_A = 0$.

tion and interest rates must be assumed. If these values are assumed to be 4 percent and 8 percent respectively, then

$R = 1.04/1.08 = 0.9630.$

The computations with Equation (1) are as follows:

$$t_B = \ln(0.9630^0 - 35(1-0.9630^{40})/(60+35(0.9630^{20}+0.9630^{30})/\ln(0.9630)$$

$$t_B = 9.9$$

To be cost effective, therefore, System 1 (membrane and overlay) must be capable of delaying the complete reconstruction of the bridge deck by 10 years or more.

Next, it is necessary to check the degree to which this result is sensitive to the assumed values for inflation and interest. Suppose, for example, that both climbed back to the peak values of the last decade of about 10 and 15 percent, respectively. In this case, $R = 1.10/1.15 = 0.9565$. When this value is used in place of $R = 0.9630$ in Equation (1), the required life of System 1 becomes $t_B = 9.6$ years. It is apparent that the result is not greatly sensitive to inflation and interest rates as long as the two move approximately in parallel, as is usually the case. This is an important finding because it means the procedure can be used with confidence even though interest and inflation rates can never be predicted with great certainty.

It is also of interest to determine how much System 2 (latex modified concrete overlay) and System 3 (cathodic protection with a latex modified concrete overlay) must delay the complete reconstruction in order to justify their use. Using the original value of $R = 0.9630$ in Equation (1), required delays of 11.6 and 13.5 years are obtained, respectively.

In summary, if any of Systems 1, 2 or 3 are being considered as a delaying tactic in lieu of impending reconstruction, the required lives of these systems would need to be at least 10, 12 or 14 years, respectively, to be economically justifiable.

4.2.2 Comparisons of Systems 1, 2, and 3

There may be instances in which a complete reconstruction is desirable but, for one reason or another, cannot be undertaken at the present time. In this case, some sort of intermediate repair will be necessary and a choice among Systems 1, 2, and 3 may have to be made. For example, if it were felt that System 1 would have an expected life of 10 years for a particular application, and System 3 were also under consideration, System 3 is economically justifiable if it is capable of lasting at least 13.7 years. Similarly, if System 2 had been proposed with an expected life of 20 years, and consideration were being given to downgrading to System 1, this would be economically justifiable only if System 1 would last at least 17.6 years under the same conditions.

4.2.3 Comments on Analysis

Although the results presented in Section 4.2.2 are not strongly dependent upon interest and inflation rates, they are dependent upon the relative magnitudes of the total in-place costs for the various repair strategies. Other agencies contemplating the use of this or any similar analysis method should take care to use costs appropriate for their applications and locales.

PART FIVE: RECOMMENDATIONS FOR FUTURE USE

Based on the findings in this study, existing repair and protection guidelines and available literature, recommendations for future use of the studied systems as well as cathodic protection are presented in the following table.

RECOMMENDED ALTERNATIVE STRATEGY FOR SELECTION OF PROTECTIVE SYSTEM

CONDITION * CATEGORY: CRITERION	COMPLETE DECK REPLACEMENT	LATEX MODIFIED CONCRETE OVERLAY	MEMBRANE W/ BITUMINOUS CONCRETE OVERLAY	CATHODIC PROTECTION
STRUCTURALLY INADEQUATE	X			
EXTENSIVE DECK DETERIORATION	X	X		X
MODERATE DECK DETERIORATION: Interstate/ Primary Route		X		X
Secondary Route		X	X	
LIGHT DECK DETERIORATION: Interstate/ Primary Route		X		X
Secondary Route		X	X	
Remaining life of structure less than 10 years			X	
Moderate to heavy scaling exceeding 10% of deck area; poor air void system		X		

* Based on NJDOT criteria (see Appendix F).

PART SIX: REFERENCES

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APPENDIX A

LIST OF TEST BRIDGES

APPENDIX A: LIST OF TEST BRIDGES

TEST SITE NO.	BRIDGE IDENTIFICATION (Orig. Constr. Date)	DECK DESCRIPTION/ DIMENSIONS	LOCATION	TWO-WAY AADT	PROTECTIVE SYSTEM (Installation Date)
1	RT. U.S. 46, WB OVER PAULISON AVE. STRUCTURE NO. 1607158 (1939)	#LANES;SPANS:2;1 LENGTH: 54' WIDTH: 24'	CLIFTON CITY PASSAIC COUNTY	45,000	UNIROYAL HOT-APPLIED LIQUID RUBBERIZED ASPHALT MEMBRANE (July 1972)
2	RT. NJ 64, WB OVER PENN. R.R. STRUCTURE NO. 1117150 (1938)	#LANES;SPANS:2;1 LENGTH: 109' WIDTH: 24'	W.WINDSOR TWP. MERCER COUNTY	9,000	ROYSTON PRE-FORMED SHEET MEMBRANE (Oct. 1972)
3	RT. NJ 64, EB OVER PENN. R.R. STRUCTURE NO. 1117150 (1938)	(SAME	AS	ABOVE)	W.R. GRACE PREFORMED SHEET MEMBRANE (Oct. 1972)
4	RT. NJ 70, EB OVER CENTRAL R.R. (1938)	#LANES;SPANS:2;3 LENGTH: 165' WIDTH: 26'	MANCHESTER TWP OCEAN COUNTY	14,500	PHILLIPS TACK COAT MEMBRANE (PETROMAT) (Aug. 1975)
5	RT. I-287, NB OVER RT. U.S. 46 STRUCTURE NO. 1420157 (1963)	#LANES;SPANS:2;4 LENGTH: 237'-6" WIDTH: 53'-6"	PARSIPPANY-TROY HILLS TWP MORRIS COUNTY	30,000	DOW SM-100 LATEX MOD. CONC. OVERLAY (1976)
6	MOUNTAIN AVE. OVER PETER'S BROOK STRUCTURE NO. 18FB509 (unknown)	#LANES;SPANS:2;2 LENGTH: 78' WIDTH: 34'-6"	SOMERVILLE BORO SOMERSET COUNTY	2,000	IOWA SYSTEM LSHD CONC. OVERLAY (May 1977)

APPENDIX A: LIST OF TEST BRIDGES (cont'd)

TEST SITE NO.	BRIDGE IDENTIFICATION (Orig. Constr. Date)	DECK DESCRIPTION/ DIMENSIONS	LOCATION	TWO-WAY AADT	PROTECTIVE SYSTEM (Installation Date)
7	RT. U.S. 22, EB VIA-DUCT OVER LIBERTY ST. AND LEHIGH VALLEY R.R STRUCTURE NO.2004-153	#LANES;SPANS:3;15 LENGTH: 700' WIDTH: 38'	HILLSIDE TWP. UNION COUNTY	65,000	ROYSTON NO. 10 PRE-FORMED SHEET MEMBRANE (Nov. 1977)
8	BLOY ST. OVER RT. U.S. 22 STRUCTURE NO.2004-152 (1940)	#LANES;SPANS:2;1 LENGTH: 77' WIDTH: 30'	(SAME AS ABOVE)	15,000	W.R. GRACE PRE-FORMED SHEET MEMBRANE (Dec. 1977)
9A	RT. U.S. 22, EB OVER THE ELIZABETH RIVER STRUCTURE NO.2004-151 (1928)	#LANES;SPANS:2;1 LENGTH: 70'-6" WIDTH: 29'	(SAME AS ABOVE)	66,000	W.R. GRACE PRE-FORMED SHEET MEMBRANE (Aug. 1978)
9B	RT. U.S. 22, WB OVER THE ELIZABETH RIVER STRUCTURE NO.2004-151 (1928)	(SAME	AS		ABOVE)
10	RT. NJ 35 OVER THE NAVESINK RIVER STRUCTURE NO.1312-154 (1925)	#LANES;SPANS:4;14 LENGTH: 924'-6" WIDTH: 38'-6"	MIDDLETOWN TWP MONMOUTH C'NTY	20,000	ROYSTON NO. 10 PRE-FORMED SHEET MEMBRANE (Nov. 1977)
11	RT. I-195, EB OVER RT. U.S. 130 STRUCTURE NO.1134-164 (1972)	#LANES;SPANS:3;2 LENGTH: 208' WIDTH: 52'	HAMILTON TWP. MERCER COUNTY	15,000	CHEM-TRETE SILANE SURFACE TREAMENT (Nov. 1982)

TEST SITE NO.	BRIDGE IDENTIFICATION (Orig. Constr. Date)	DECK DESCRIPTION/ DIMENSIONS	LOCATION	TWO-WAY AADT	PROTECTIVE SYSTEM (Installation Date)
12	RT. I-195, WB OVER RT. U.S. 130 STRUCTURE NO.1134-164 (1972)	#LANES;SPANS:3;2 LENGTH: 208' WIDTH: 52'	HAMILTON TWP. MERCER COUNTY	15,000	DYLEX LATEX MODIFIED CONCRETE OVERLAY (Nov. 1982)
13	RT. I-195, EB OVER THE NJ TURNPIKE STRUCTURE NO.1134-167 (1973)	#LANES;SPANS:3;2 LENGTH: 297' WIDTH: 42'-6"	WASHINGTON TWP MERCER COUNTY	15,000	CHEM-TRETE SILANE SURFACE TREATMENT (Nov. 1982)
14	RT. I-195, WB OVER THE NJ TURNPIKE STRUCTURE NO.1134-151 (1973)	#LANES;SPANS:2;4 LENGTH: 290' WIDTH: 42'-6"	(SAME AS ABOVE)		DYLEX LATEX MODIFIED CONCRETE OVERLAY (Nov. 1982)

APPENDIX B

SUMMARY OF FINAL PERFORMANCE TESTING EVALUATION

APPENDIX B: SUMMARY OF FINAL PERFORMANCE TESTING EVALUATION

TEST SITE NO. PROTECTIVE SYSTEM	YEARS IN SERVICE	VISUAL ASSESSMENT	CHLORIDE CONTENT(lbs/cy) AVERAGE	RANGE	% SAMPLES >2.0[a]	% ELECTRICAL POTENTIAL MEASUREMENTS >0.35v[b]	% ELECTRICAL RESISTANCE MEASUREMENTS <100kΩ[c]
1 MEMBRANE W/ BITUMINOUS OVERLAY	13	WEARING SURFACE: Moderate rutting; some fine to wide transverse cracking; 1 s.f. area of deteriorated asphalt (1/2" deep). CONCRETE DECK: Light scaling; one small delaminated area; dry. UNDERSIDE: Considerable fine to medium cracking with efflorescence evidence of leakage at joints.	5.4 (N=4)	2.1-9.5	25	N/A	40
2 MEMBRANE W/ BITUMINOUS OVERLAY	13	WEARING SURFACE: Moderate to severe rutting; considerable fine to medium cracking; several deteriorated areas w/ 1 s.f. area exposing membrane, several patches; depressions. CONCRETE DECK: One small delaminated area; wet. UNDERSIDE: (Same as Site No.1, w/ some spalling).	4.0 (N=4)	3.6-4.9	100	N/A	70
3 MEMBRANE W/ BITUMINOUS OVERLAY	13	WEARING SURFACE: Moderate to severe rutting; considerable cracking(sealed); 3/4" settlement at joints, w/patching; several deteriorated areas. CONCRETE DECK: One small delaminated area; dry. UNDERSIDE: (Same as Site #1); two spalled areas w/ exposed, rusted rebars.	5.8 (N=4)	2.9-8.1	100	N/A	70

Notes: [a] Threshold level at which it is likely corrosion will occur.
[b] Measurements >0.35v indicate corrosion.
[c] Measurements <100kΩ indicate poor performance (moisture present).

APPENDIX B: SUMMARY OF FINAL PERFORMANCE TESTING EVALUATION (cont'd)

TEST SITE NO. PROTECTIVE SYSTEM	YEARS IN SERVICE	VISUAL ASSESSMENT	CHLORIDE CONTENT (lbs/cy)			% ELECTRICAL POTENTIAL MEASUREMENTS >0.35v [b]	% ELECTRICAL RESISTANCE MEASUREMENTS <100kΩ [c]
			AVERAGE	RANGE	% SAMPLES >2.0 [a]		
4 MEMBRANE W/ BITUMINOUS OVERLAY	10	WEARING SURFACE: Moderate to severe rutting; fine to medium cracking; several patches; 2 s.f. area of deteriorated asphalt; shoving and depressions. CONCRETE DECK: Delaminations; scaling; spalling; wet. UNDERSIDE: Fine cracking w/efflorescence; spalling; exposed rebars.	1.9 (N=7)	1.4-2.9	30	N/A	----
5 LATEX MODIFIED CONCRETE OVERLAY	9	WEARING SURFACE: Light to moderate scaling; fine to medium cracking; spalling; several patches; delaminations. UNDERSIDE: Fine to medium cracking w/effloresence; evidence of leakage at joints.	3.3 (N=15)	0.6-7.7	73	36	100
6 LSHD CONCRETE OVERLAY	9	WEARING SURFACE: Light to moderate scaling; fine cracking & several sealed cracks running full length & width. UNDERSIDE: Evidence of leakage.	1.0 (N=10)	0.6-2.0	0	0	80
7 MEMBRANE W/ BITUMINOUS OVERLAY	8	WEARING SURFACE: Moderate rutting; extensive fine to medium cracking; several patches; shoving; depressions; several deteriorated areas. CONCRETE DECK: Moderate to heavy scaling; delaminations; wet. UNDERSIDE: Extensive fine to medium cracking w/effloresence; evidence of leakage.	1.5 (N=12)	0.3-3.8	42	N/A	32

Notes: [a] Threshold level at which it is likely corrosion will occur.
[b] Measurements >0.35v indicate corrosion.
[c] Measurements <100kΩ indicate poor performance (moisture present).

APPENDIX B: SUMMARY OF FINAL PERFORMANCE TESTING EVALUATION (cont'd)

TEST SITE NO. PROTECTIVE SYSTEM	YEARS IN SERVICE	VISUAL ASSESSMENT	CHLORIDE CONTENT(lbs/cy) AVERAGE	RANGE	% SAMPLES >2.0 [a]	% ELECTRICAL POTENTIAL MEASUREMENTS >0.35v [b]	% ELECTRICAL RESISTANCE MEASUREMENTS <100kΩ [c]
8 MEMBRANE W/ BITUMINOUS OVERLAY	8	WEARING SURFACE: Moderate to severe rutting; fine to medium cracking; several deteriorated areas; several patches; shoving; depressions. CONCRETE DECK: Moderate to heavy scaling; delaminations; wet. UNDERSIDE: Fine to medium cracking w/efflorescence; spalling;leakage.	2.8 (N=4)	2.4-3.4	100	N/A	30
9A MEMBRANE W/ BITUMINOUS OVERLAY	7	WEARING SURFACE: Moderate rutting; fine cracking; small (5 s.f.) patch; some deterioration. CONCRETE DECK: Moderate scaling; medium cracking; wet. UNDERSIDE: Medium cracking w/efflorescence; evidence of leakage.	4.4 (N=4)	1.3-6.3	75	N/A	40
9B MEMBRANE W/ BITUMINOUS OVERLAY	7	WEARING SURFACE: (Same as 9A above) CONCRETE DECK: Light scaling; wet. UNDERSIDE: (Same as 9A above).	3.0 (N=3)	0.9-2.4	33	N/A	40
10 MEMBRANE W/ BITUMINOUS OVERLAY	8	WEARING SURFACE: Moderate rutting; medium cracking; depressions. CONCRETE DECK: Light to moderate scaling; delaminations; dry. UNDERSIDE: Extensive spalling; exposed rebars; fine to medium cracking w/efflorescence.	3.6 (N=9)	0.3-8.8	56	N/A	58

Notes: [a] Threshold level at which it is likely corrosion will occur.
[b] Measurements >0.35v indicate corrosion.
[c] Measurements <100kΩ indicate poor performance (moisture present).

APPENDIX B: SUMMARY OF FINAL PERFORMANCE TESTING EVALUATION (cont'd)

TEST SITE NO. PROTECTIVE SYSTEM	YEARS IN SERVICE	VISUAL ASSESSMENT	CHLORIDE CONTENT(lbs/cy)			% ELECTRICAL POTENTIAL MEASUREMENTS >0.35v [b]	% ELECTRICAL RESISTANCE MEASUREMENTS <100kΩ [c]
			AVERAGE	RANGE	% SAMPLES >2.0 [a]		
11 SEALER	3	WEARING SURFACE: Light to moderate scaling; fine to medium cracking. UNDERSIDE: Some cracking; evidence of leakage.	0.8 (N=10)	0.0-2.1	10	0	100
12 LATEX MODIFIED CONCRETE OVERLAY	3	WEARING SURFACE: Good condition. UNDERSIDE: Stay-in-place forms prevented complete inspection, however, some evidence of minor leakage present.	0.7 (N=10)	0.2-1.4	0	0	100
13 SEALER	3	WEARING SURFACE: Light to moderate scaling; one small (<1 s.f.)spall; fine cracking. UNDERSIDE: (Same as Site No. 12).	0.5 (N=10)	0.2-1.0	0	0	100
14 LATEX MODIFIED CONCRETE OVERLAY	3	WEARING SURFACE: Good. UNDERSIDE: (Same as Site No. 12).	0.5 (N=10)	0.2-0.8	0	0	100

Notes: [a] Threshold level at which it is likely corrosion will occur.
[b] Measurements >0.35v indicate corrosion.
[c] Measurements <100kΩ indicate poor performance (moisture present).

APPENDIX C

Table 1: Chloride Content in Membrane-Protected Decks

Table 2: Summary of Electrical Resistance Measurements in Membrane-Protected Decks

Table 3: Chloride Content in Rigid Concrete Overlayed Decks

Table 4: Summary of Electrical Potential Measurements in Rigid Concrete Overlayed Decks

Table 5: Results of Pre-installation Survey of Sealer-Treated & Latex Modified Concrete Decks

Table 6: Sealer Application Data

Table 7: Chloride Content in Sealer-Treated Decks

Table 8: Summary of Electrical Potential Measurements in Sealer-Treated Decks

Table 9: Summary of Electrical Resistance Measurements in Sealer-Treated Decks

TABLE 1: CHLORIDE CONTENT IN MEMBRANE-PROTECTED DECKS

INSTALLATION DATE	TEST SITE NO.	YEARS IN SERVICE	NO. SAMPLES	CHLORIDE CONTENT (lbs/cy)			
				AVERAGE	RANGE	% SAMPLES 1.1[a]-2.0	%SAMPLES >2.0[b]
1972	1-3	13	12	3.6	0.5-9.5	1	75
1975	4	10	7	1.9	1.4-2.9	70	30
1977	7,8&10	(c)	30	3.7	0.4-9.7	10	60
		8	25	2.5	0.3-8.8	0	57
1978	9A&B	(c)	10	2.6	0.8-6.3	20	40
		7	7	3.8	0.9-6.3	29	57

NOTES: [a] Threshold level considered sufficient to initiate corrosion.
[b] Threshold level at which it is likely corrosion will occur.
[c] Prior to system installation.

TABLE 2: SUMMARY OF ELECTRICAL RESISTANCE MEASUREMENTS IN MEMBRANE-PROTECTED DECKS

YEARS IN SERVICE	TEST SITE NO.	NO. MEASUREMENTS	PERCENTILES (ohms)			MEDIAN (ohms)
			>500k[a]	500-100k[b]	<100k[c]	
NEW	7,8 & 10	49	45	27	28	3×10^6
1	7	50	48	28	24	5×10^5
2	9A&B	10	60	20	20	6×10^5
3	7,8 & 10	89	46	17	37	14×10^6
4	8,9A&B	20	60	20	20	∞
5	7 & 10	79	40	18	32	12×10^6
6	9A&B	10	70	0	30	∞
7	7,8 & 10	50	44	12	44	2×10^6
8	7,8 & 10	50	32	16	56	5×10^4
10	4	10	90	10	0	∞
11	1-3	30	33	17	50	3×10^5
12	1-3	30	30	10	60	3×10^5
13	1-3	30	30	10	60	2×10^5

Notes: Performance levels (Percentiles)
[a] Excellent
[b] Questionable
[c] Poor (moisture present).

TABLE 3: CHLORIDE CONTENT IN RIGID CONCRETE OVERLAYED DECKS

INSTALLATION DATE	TEST SITE NO.	YEARS IN SERVICE	NO. SAMPLES	CHLORIDE CONTENT (lbs/cy)			
				AVERAGE	RANGE	% SAMPLES 1.1[a]-2.0	%SAMPLES >2.0[b]
1976 (IMC)	5	9	15	3.4	0.6-7.7	15	73
1977 (LSHD)	6	8	10	1.0	0.6-2.0	40	0
1982 (IMC)	12&14	(c)	20	0.6	0.1-2.4	5	5
		2	20	0.5	0.0-1.0	0	0
		3	20	0.6	0.2-1.4	5	0

NOTES: [a] Threshold level considered sufficient to initiate corrosion.
[b] Threshold level at which it is likely that corrosion will occur.
[c] Prior to system installation.

TABLE 4: SUMMARY OF ELECTRICAL POTENTIAL MEASUREMENTS IN RIGID CONCRETE OVERLAYED DECKS

YEARS IN SERVICE	TEST SITE NO. / SYSTEM	NO. MEASUREMENTS	PERCENTILES (volts)			MEAN (volts)
			<0.20[b]	0.20-0.35[c]	>0.35[d]	
(a)	12 & 14 LMC	180	89	11	0	0.13
1	12 & 14 LMC	180	100	0	0	0.11
2	12 & 14 LMC	180	100	0	0	0.08
3	12 & 14 LMC	181	100	0	0	0.09
5	5 LMC	235	71	26	3	0.16
7	5 LMC	240	20	60	20	0.22
8	5 LMC	240	33	42	25	0.26
9	5 LMC	240	21	43	36	0.28
4	6 LSHD	86	95	5	0	0.21
6	6 LSHD	86	57	43	0	0.24
7	6 LSHD	86	67	33	0	0.18
8	6 LSHD	86	83	17	0	0.14

NOTES: [a] Prior to system installation.

Corrosion activity (Percentiles)

[b] Improbable
[c] Questionable
[d] Probable

TABLE 6: SEALER APPLICATION DATA

TEST SITE NO.	DATE OF APPLICATION	WEATHER AND TEMPERATURE	AREA COVERED (s.f.)	COVERAGE RATE (s.f./gal.)	REMARKS
11	11-03-82	Overcast, 73° F	7,308	125	Surfaces damp
	11-16-82	Clear, 28° F	8,469	125	----
13	11-11-82	Clear, 54° F	7,128	124	----
	11-19-82	Overcast, 58° F	5,829	122	----

TABLE 7: CHLORIDE CONTENT IN SEALER-TREATED DECKS
(Test Sites 11 & 13)

YEARS IN SERVICE	CHLORIDE CONTENT DATA (lbs/cy)					
	DEPTH (inches)	AVERAGE	RANGE	NO. SAMPLES	%SAMPLES 1.1[a]-2.0	%SAMPLES >2.0[b]
(c)	SURFACE TO 1	2.0	0.5-4.0	20	20	45
	1-2	1.0	0.2-2.6	20	35	5
2	SURFACE TO 1	2.3	0.9-4.3	20	50	45
	1-2	1.0	0.3-2.1	20	30	5
3	SURFACE TO 1	1.6	0.6-3.0	20	50	20
	1-2	0.7	0.2-2.1	20	10	5

Notes: [a] Threshold level considered sufficient to intitiate corrosion.
[b] Threshold level at which it is likely corrosion will occur.
[c] Prior to system installation.

TABLE 7: CHLORIDE CONTENT IN SEALER-TREATED DECKS
(Test Sites 11 & 13)

YEARS IN SERVICE	CHLORIDE CONTENT DATA (lbs/cy)					
	DEPTH (inches)	AVERAGE	RANGE	NO. SAMPLES	%SAMPLES 1.1[a]-2.0	%SAMPLES >2.0[b]
(c)	SURFACE TO 1	2.0	0.5-4.0	20	20	45
	1-2	1.0	0.2-2.6	20	35	5
2	SURFACE TO 1	2.3	0.9-4.3	20	50	45
	1-2	1.0	0.3-2.1	20	30	5
3	SURFACE TO 1	1.6	0.6-3.0	20	50	20
	1-2	0.7	0.2-2.1	20	10	5

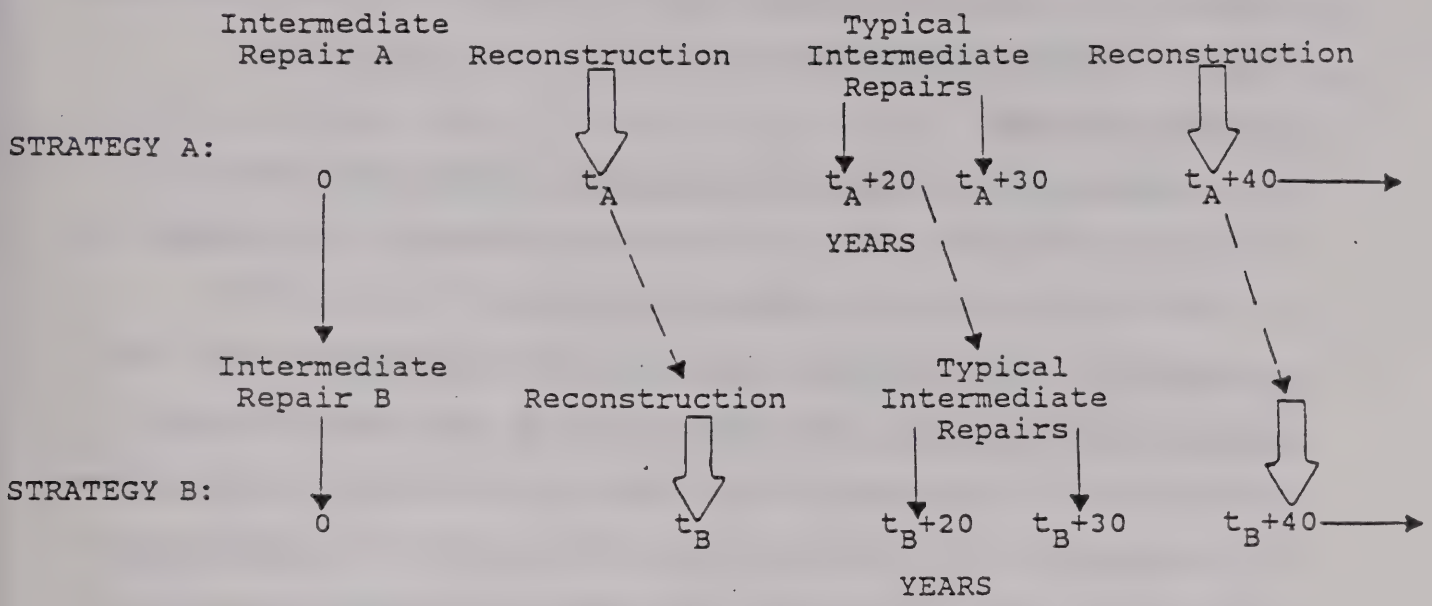
Notes: [a] Threshold level considered sufficient to intitiate corrosion.
[b] Threshold level at which it is likely corrosion will occur.
[c] Prior to system installation.

APPENDIX D

DERIVATION OF ECONOMIC ANALYSIS EQUATION

APPENDIX D: DERIVATION OF EQUATION #1

Activity Diagram



Objective

To determine the necessary forestalling (t_A-t_B) of the stream of activities beginning with the first reconstruction to justify the higher cost of Intermediate Repair B at time zero. The derivation that follows may be generalized to include a "do nothing" strategy in which case $t_A = 0$.

Assumptions

In order to perform the analysis, certain assumptions must be made and a model created that depicts the sequence of the various repair activities. The basic assumptions are shown in the above activity diagram. The large arrows represent complete reconstructions and the distance between the large arrows

indicates the assumed typical design life of a bridge of 40 years. The small arrows represent intermediate repairs, typically a membrane and an overlay, and are assumed to fall at the 20th and 30th years of the design life of the bridge. Costs to be used are $60/s.f. for complete reconstruction and $35/s.f. for intermediate repair as discussed on Section 4.2.

Economic Concept

Because of the time value of money, there is a value associated with the delay of any major expense. The dashed lines in the activity diagram indicate the delay of $t_B - t_A$ years associated with the entire stream of events beginning with the first reconstruction. This represents an infinite series of events which is appropriate for analytical purposes provided there is no reason to believe the bridge will cease to be required in the future. The analysis will be practically useful as long as the results are not highly sensitive to the interest and inflation rates that are being projected a great distance into the future.

In order to compare all activities throughout a period of time on an equal basis, it is conventional to express each in terms of its present worth. This requires that appropriate interest and inflation rates (or, equivalently, a discount rate) be assumed. A convenient expression[19] for this purpose is given by:

$$W_0 = C_0 R^t \qquad (1)$$

in which

W_0 = present worth

C_0 = present cost

$$R = (1+R_{inf}/100)/(1+R_{int}/100)$$

R_{inf} = average long-term annual inflation rate, percent

R_{int} = average long-term annual interest rate, percent

t = number of years in the future that an activity takes place

If an expense that would have occurred t_A years in the future can be delayed until t_B years in the future, the present worth of this delay represents a savings (S) that is computed by use of Equation (1) to be

$$S = C_0 \ (R^{tA}-R^{tB}) \qquad (2)$$

This expression will be used to sum the individual savings associated with the delay of each of the events in the activity diagram.

Derivation

Using equation (2), the sum of the savings associated with the individual actions in the activity diagram can be written as follows:

$$S = 60(R^{tA-}R^{tB})+35(R^{tA+20}-R^{tB+20})+35(R^{tA+30}-R^{tB+30})$$

$$+60(R^{tA+40}-R^{tB+40})+35(R^{tA+60}-R^{tB+60})+35(R^{tA+70}-R^{tB+70})$$

$$+60(R^{tA+80}-R^{tB+80})+... \qquad (3)$$

This can be simplified to become

$$S = 60(R^{tA}-R^{tB})+35R^{20}(R^{tA}-R^{tB})+35R^{30}(R^{tA}-R^{tB})$$

$$+60R^{40}(R^{tA}-R^{tB})+35R^{60}(R^{tA}-R^{tB})+35R^{70}(R^{tA}-R^{tB})$$

$$+60R^{80}(R^{tA}-R^{tB})+... \quad (4)$$

Factoring this expression then produces

$$S = (R^{tA}-R^{tB})[60(1+R^{40}+R^{80}+...)+35(R^{20}+R^{30}+R^{60}+R^{70}+...)] \quad (5)$$

Next, a closed-form solution must be found for the two terms representing infinite series:

Let $S_1 = 1+R^{40}+R^{80}+...+R^{oo}$ (6)

Then if both sides are multiplied by R^{40},

then $S_1R^{40}=R^{40}+R^{80}+...+R^{oo}+R^{oo+40}$ (7)

and, by subtracting Equation (7) from Equation (6),

$$S_1(1-R^{40})=1-R^{oo+40} \quad (8)$$

But R is a fraction less than unity so R^{oo+40} 0.

therefore, $S_1=1/(1-R^{40})$ (9)

Let $S_2 = R^{20}+R^{30}+R^{60}+R^{70}+...+R^{oo+20}+R^{oo+30}$ (10)

then $S_2R^{40} = R^{60}+R^{70}+...+R^{oo+20}+R^{oo+30}+R^{oo+60}$

$+R^{oo+70}$ (11)

and $S_2(1-R^{40})=R^{20}+R^{30}-R^{oo+60}-R^{oo+70}=R^{20}+R^{30}$

(12)

therefore $S_2 = (R^{20}+R^{30})/(1-R^{40})$

(13)

Then by substituting Equations (9) and (13) into Equation (5), a closed-form solution is obtained:

$$S = (R^{tA}-R^{tB})(60+35(R^{20}+R^{30}))/(1-R^{40}) \quad (14)$$

Finally, Equation (14) must be solved for t_B to determine the required life of Intermediate Repair B to be exactly equal in economic value to Intermediate Repair A. In other words, the present worth (S) of delaying the stream of various repair activities must exactly equal the difference in cost (D) between the two candidate repair strategies.

$$D=(R^{tA}-R^{tB})(60+35(R^{20}+R^{30}))/(1-R^{40}) \quad (15)$$

Transposing and rearranging:

$$R^{tB}=R^{tA}-D(1-R^{40})/(60+35(R^{20}+R^{30})) \quad (16)$$

Logarithms are then taken to solve for t_B:

$$t_B=\ln(R^{tA}-D(1-R^{40})/(60+35(R^{20}+R^{30})))/\ln(R) \quad (17)$$

APPENDIX E

NJDOT RECOMMENDED RESTORATION PROCEDURES

APPENDIX E: NJDOT RECOMMENDED RESTORATION PROCEDURES

TESTING STEPS
1. Visual
2. Delamination
3. Elect. Potential
4. Rebar Depth
5. Chloride Content

ACCEPTABLE RESTORATION PROCEDURES

CATEGORY	PROCEDURES	RESTORATION (Considered Permanent)	RESTORATION (Estimated Extended Life 10 to 15 years)
Structurally Inadequate		Complete Deck Replacement (Unless restorable)	
Extensive Deck Deterioration (1)	Required Restoration Work	Complete Deck Replacement	Removal of all deteriorated concrete. Follow the repair procedure approved for the protective system selected.
	Testing	Steps #1 thru 5 as necessary Probably only Step #1 & 2	Steps #1 & 2 only. (All steps on the first 5 plus 10% of the remaining decks).
	Suggested Protective System	Membrane w/bc overlay* Latex Modified Concrete Overlay Cathodic Protection* Epoxy Coated Rebars	Membrane w/bc overlay * Latex Modified Concrete overlay Cathodic Protection *
Moderate Deck Deterioration (2)		Same as for Category #1 above OR Same as for Category #3 below as determined by the State	Same as for Category #1
Light Deck Deterioration (3)	Required Restoration Work	Removal and Replacement of all areas of deterioration and chloride contaminated concrete as determined by corrosion potentials and/or chloride sampling. (Less than 5% of deck area).	Same as for Category #1 above. NOTE: For this category of condition, permanent restoration is recommended.
	Testing	Steps #1 thru 5	Steps #1 & 2 only. (All steps on the first 5 plus 10% of the remaining decks)
	Suggested Protective System	Membrane w/bc overlay * Cathodic Protection * Latex Modified Concrete Overlay	Membrane w/bc overlay * Cathodic Protection * Latex Modified Concrete Overlay

* When approved prior to Phase 2 Plan Submission on a project to project basis.

APPENDIX F

NJDOT RECOMMENDED GUIDE FOR BRIDGE DECK CONDITION EVALUATION

APPENDIX F: NJDOT RECOMMENDED GUIDE FOR BRIDGE DECK CONDITION RATING[21]

CONDITION RATING (ITEM 58)

CONCRETE BRIDGE DECK EVALUATION

			Condition Indicators (%deck area)		
Category Classification	Rating	Spalls	Delaminations	Electrical Potentials (volts)	Chloride Content (lbs/cy)
Category #3 Light Deterioration	9	none	none	0	0
	8	none	none	none>0.35	none>1.0
	7	none	<2%	45%<0.35	none>2.0
Category #2 Moderate Deterioration	6	<2% spalls or sum of all deteriorated and/or contaminated deck concrete <20%			
	5	<5% spalls or sum of all deteriorated and/or contaminated deck concrete 20-40%			
Category #1 Extensive Deterioration	4	>5% spalls or sum of all deteriorated and/or contaminated deck concrete 40-60%			
	3	>5% spalls or sum of all deteriorated and/or contaminated deck concrete >60%			
Structurally Inadequate Deck	2	Deck structural capacity grossly inadequate			
	1	Deck has failed completely Repairable by replacement only			
	0	Holes in deck--danger of other sections of deck failing			

Note: This specialized table can be used as a guide for evalua-
deck conditions using different condition indicators.

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